LIFE CYCLE ASSESSMENT OF END-OF-LIFE SCENARIOS: TABLET CASE STUDY

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SUMMARY: This work presents a case study for a tablet treated in France. The objective was to assess the impacts of the end-of-life stage and its influence in the final results when considering different waste management scenarios. After a first analysis of the global electronic waste management scenario, three scenarios were selected: (1) optimistic scenario, in which the tablet is recycled considering the best available technologies; (2) a conservative scenario, which considers only the best referenced recycling channels; (3) a pessimist scenario considering the worst situation in terms of recycling. For some impact categories, the recycling activities result in higher environmental impacts than the scenarios with poor recycling, among others due to the increase in energy consumption during recycling. When the benefits of recycling are considered in the assessment, the advantage of recycling is evident, reinforcing the importance of the recycling channels as a provider of secondary materials that have lower environmental impacts. The differences in the results of the three scenarios reinforce the importance of clearly report the scenario considered in the end-of-life.

1. INTRODUCTION

Waste of electrical and electronic equipment (WEEE) belongs to the fastest growing waste stream in the world (Kiddee, Naidu, & Wong, 2013). In 2014, 42 million tons of WEEE were globally discarded, and an amount of 50 million tons of WEEE is expected in 2018 (Balde et al., 2015). In France, it is estimated a generation of about 17 to 23 kg per year of e-waste per inhabitant (Ademe, 2015).

WEEE encompasses a particularly complex waste, and due to its toxic composition can cause environmental and health problems if not properly treated. Moreover, the production of electrical and electronic equipment (EEE) requires the use of materials with limited availability and high value added. Recycling, reuse and recovery can, therefore, avoid the extraction of new resources. This characteristic of e-waste has made it a lucrative business (Sinha, Laurenti, Singh, Malmström, & Frostell, 2016).

To address the e-waste problem, the European Union published in 2002 the WEEE Directive that provided for the creation of collection schemes aiming to increase the recycling and reuse of WEEE. Considering the continuous increase of e-waste flow, the directive was revised in 2012 and new targets and strategies were defined (Parlement Européen, 2012). In France, the WEEE directive was transposed into national legislation and the system was set up around several types of actors: producers, compliance schemes (also known as producer responsibility organizations or take back schemes), distributors, and local authorities.

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In 2015, 43% of WEEE generated in France was collected, in which 35% of this amount went to the recycling chain (Ademe, 2016), where only a part was recycled due to the availability of technology to recycle the different materials and processes losses. Factors such as sorting errors, plundering, alternative systems of collection and treatment are some of the reasons for household WEEE to be diverted from WEEE compliance schemes.

Recycling, with different levels of efficiency and sometimes involving downcycling, is the main treatment organized by the French compliance schemes, even though the waste management hierarchy indicates that waste reduction and reuse must be the preferred options in order to increase the lifetime of products and components (Manfredi & Goralczyk, 2013).

According to data available on the last report published by the French Environment and Energy Management Agency (ADEME), in 2015 all WEEE categories met the collection and recycling targets set by the Directive 2012/19/EU and the French regulation (Decree 2014-928). However, it is important to mention that the method to calculate the recycling rate proposed by the Directive, and consequently adopted in France, excludes the flows that diverge from WEEE compliance schemes, and does not consider the losses that occur during the recycling of the fractions (Parajuly, Habib, & Liu, 2016). Moreover, once the Directive sets recycling targets based on the overall mass of materials collected, it is not possible to visualize the recycling rates for the different materials (ferrous metals, nonferrous metals, plastics, critical metals, etc).

The French regulation presents challenging collection rates for the next years: 45% between 2016 and 2019, and 65% after 2019 of the total market input. In this context, efforts must be made to increase WEEE collection, growth recycling rates per material (including processes losses), as well as to stimulate reuse and reduce the environmental impacts of the recycling channel.

The objective of this paper was to assess the impacts of the end-of-life stage and its influence in the final results of life cycle assessment (LCA) studies when considering different waste management scenarios. This study is a part of a research project that aims to assess the environmental impacts and benefits of the French recycling channel, in order to improve its performance beyond the Directive targets. Section 2 presents an overview of the life cycle assessment (LCA) studies published in the literature focused in the end-of-life of EEE. The methodology used in this study is presented in section 3, and the results are reported and discussed in section 4. The main conclusions and opportunities for future works are presented in section 5.

2. LIFE CYCLE ASSESSMENT OF WEEE

Aiming to assess the environmental impacts related to the life cycle of EEE, in the past ten years, LCA studies have been published mainly in Europe, United States of America and Asia. Some studies that included the whole life cycle of EEE (e.g. Choi, Shin, Lee, & Hur, 2006; Achachlouei, Moberg, & Hochschorner, 2015) indicated that the end-of-life (EoL) is not a key stage when defining the environmental profile of EEE. However, some authors stressed that recycling could reduce the overall impact of the products (Rodrigues-Garcia; Weil, 2016). In the study developed by Song and colleagues (2013), the results showed that recovery of metals, glass, and plastic from e-waste can generate environmental benefits.

As discussed by Suckling and Lee (2015), the EoL of e-waste does not often follow the recycling route assumed in manufacturers' declarations, due to variations in human behavior that influence the return rate, and also to the diverse degree of development of the collection schemes in different countries. Achachlouei and colleagues (2015) stated that the lack of data makes difficult to model the EoL and increase the results uncertainties.

The transport during the end-of-life management is either not considered or the distances are estimated and not necessarily in accordance with the reality (Barba-Gutiérrez, Adenso-Diaz, & Hopp, 2008). According to Menikpura and colleagues (2014), the logistic chain accounts for a significant amount of greenhouse gas emissions in EoL of e-waste. Choi and colleagues (2006) had similar conclusions of the impact of WEEE collection in the EoL of a computer.

3. METHOD

3.1 Goal and scope

The functional unit considered in the study was: treating 1 ton of tablet in France. The composition of the tablet was determined based on a manufacturer declaration (Apple Inc., 2011), and is presented in Table 1:

Table 1. Tablet composition

Components	Mass of 1 tablet (kg)	1 ton of tablet (kg)
Liquid Cristal Display (LCD)	0.245	415.3
Aluminum alloy (back panel)	0.135	228.8
Battery Lithium-ion	0.130	220.3
PCB and connectors	0.038	64.4
Other metals*	0.025	42.4
Plastics	0.017	28.8
Total	0.590	1000

* Due to absence of data, in this study the "other metals" were considered as 33% aluminum, 33% copper and 33% iron.

After a first analysis of the French recycling channel, three scenarios were selected: (1) optimistic scenario, in which the tablet is recycled considering the best available technologies; (2) a conservative scenario, which considers only the best referenced recycling channels; (3) a pessimist scenario considering the worst situation in terms of recycling. The optimistic and the conservative scenarios considered the manual dismantling of the tablet followed by the treatment of its components. These scenarios comply with the requirements of the WEEE Directive regarding the decontamination before treatment, considering the presence of a battery and that the LCD module has a surface area greater than 100 cm^2. In the pessimist scenario, the tablet was considered to be shredded with other small equipment followed by sorting and recycling of classical metals. The scenarios are detailed in Table 2.

The system boundaries of the LCA comprises the different steps of the e-waste treatment (dismantling, shredding, sorting, recycling, landfilling and/or incineration), excluding the transport (Figure 1). This work focuses on the impact of the treatment processes, and the transport was not considered due to lack of primary data. Considering the conclusions related to the impact of transport of some studies, the authors intend to include it in future works.

Table 2. EoL scenarios

Components	Optimistic scenario	Conservative scenario	Pessimist scenario
LCD	Recycling of the glass and landfill of LCD module	Landfill	Tablet shredded mixed with small equipment followed by sorting and recycling of classical metals (iron, copper and aluminum)
Aluminum alloy	Shredding, sorting and recycling	Shredding, sorting and recycling	
Battery Lithium-ion	Manual sorting and recycling	Manual sorting and recycling	
Printed Circuit Boards (PCB)	Manual sorting, recycling of precious metals and plastic incineration with energy recovery	Manual sorting, recycling of precious metals and plastic incineration with energy recovery	
Other metals	Shredding, sorting and recycling	Shredding, sorting and recycling	
Plastics	Shredding, sorting and recycling	Shredding and treated with the sorting losses	
Sorting and recycling losses	Incineration with energy recovery	Landfill	Landfill

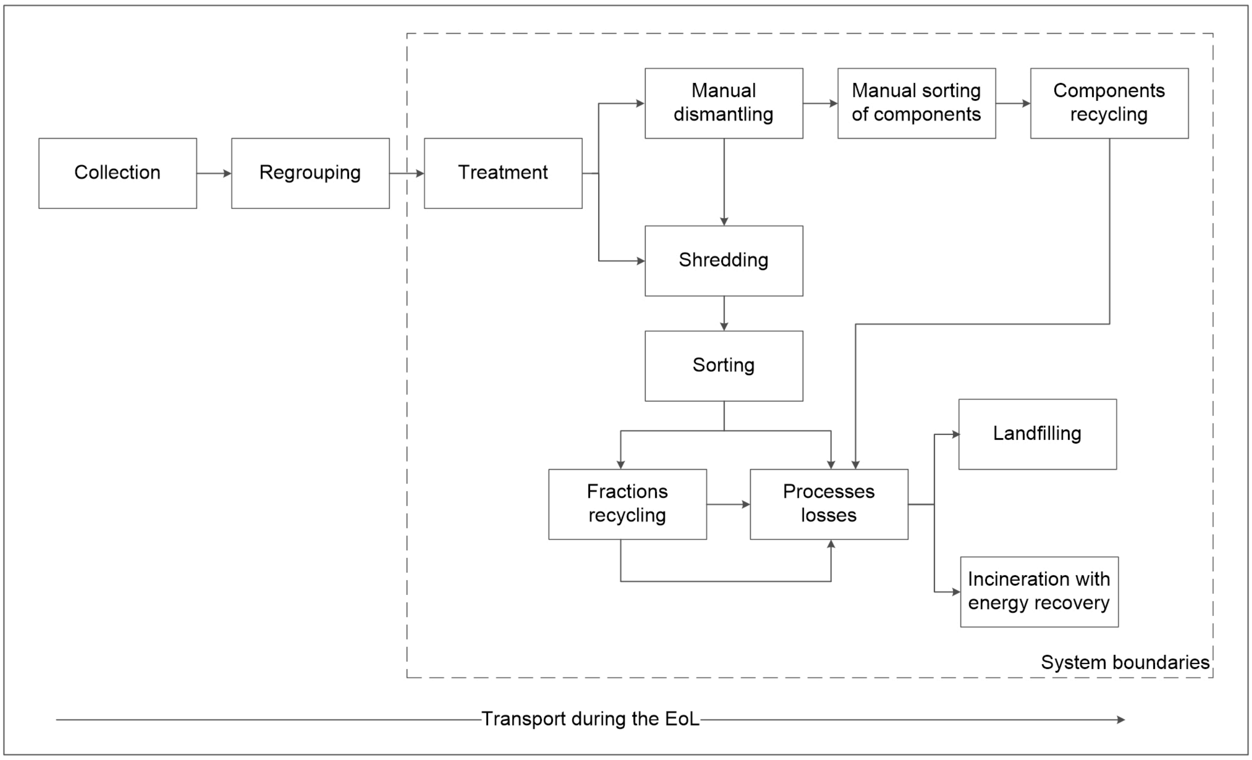

Figure 1. System boundaries of the study

3.2 Life Cycle Inventory

Life cycle inventory (LCI) for each scenario was developed based on the inventories available in Ecoinvent database (version 3.2, recycled content dataset) and adapted with literature and primary data obtained in discussions with specialists and recyclers. The main adaptations were:

- Efficiency rate of separation after shredding, in order to account for processes losses (Hischier, Classen, Lehmann, & Scharnhorst, 2007);
- Recycling rate of metals and plastics (Hischier, Classen, Lehmann, & Scharnhorst, 2007; Eurometaux & Eurofer, 2012; Makenji and Saveji, 2012; Valero Navazo, Villalba Méndez, & Talens Peiró, 2013; International Copper Association, 2014)
- Energy consumption for sorting the plastics in the optimist scenario, considering the near infrared and optical sorting techniques (Shonfield, 2008);
- Landfill scenarios assessed according to the methodology developed by Doka (2007).
- Energy recovery of the materials incinerated (processes losses in the optimistic scenario, and plastics of printed circuit board in optimistic and conservative scenarios).

3.3 Life Cycle Impact Assessment

According to Rodrigues-Garcia and Weil (2016), the life cycle impact assessment (LCIA) methodologies more widely used in LCA of WEEE are CML 2001 and Eco-Indicator (95 or 99). Considering that these methods are superseded and that the European Commission released a methodology for LCIA in the European context, the LCIA results were calculated at midpoint level by using the ILCD 2011 adapted with the IPCC version 1.02. The impact categories selected were: global warming potential, human toxicity potential (non-cancer and cancer effects), freshwater ecotoxicity potential and mineral, fossil and renewable resource depletion potential. The set of impact categories selected allows fulfillment of the requirement of ISO standards which prescribes a selection of impact categories that reflects a comprehensive set of environmental issues related to the product system.

The life cycle impact assessment (LCIA) was performed in two steps: firstly, the environmental impacts of the EoL scenarios were assessed; then, in order to assess the benefits of recycling as a potential reducer of new resources extraction, they were compared to the environmental impacts of producing the same amount of virgin materials than the recycled one in each EoL scenario. This approach was selected once the recycled materials have the same or closely resembles the inherent properties of the primary materials (closed loop recycling) (Ligthart & Ansems, 2012). In the following section, the results are reported and discussed.

4. RESULTS AND DISCUSSION

Considering the treatment of each component of the tablet in the three scenarios presented in Table 2 and the recycling rates of the materials, the percentage of the tablet effectively recycled in each scenario is presented in Table 3.

Table 3. Percentage of the tablet treated by type of treatment

Type of Treatment	Optimistic scenario (%)	Conservative scenario (%)	Pessimist scenario (%)
Recycling	54.9	38.5	21.5
Landfilling	34.1	56.8	78.5
Incineration with energy recovery	11.0	4.7	0.0

When comparing the results of the scenarios to the targets set by the Directive for category 3 (IT and telecommunications equipment) from 2015 until 2018 (80% shall be recovered and 70% recycled or reused), even the optimistic scenario do not comply with the targets. These results stress the need for improving recycling and also the design of new products in order to facilitate its treatment in the end-of-life. Due to lack of LCI data, the LCD module recycling (which includes the recycling of precious metals like indium), could not be taken into account. If the recycling of the LCD module had been considered, the optimistic scenario would probably achieve the targets (the LCD module represents 25.7% of the tablets mass).

As presented in Table 4 and Figure 2**,** the different EoL scenarios resulted in diverse environmental impacts. For human toxicity (non-cancer effects), the pessimist scenario entails a result ten times higher than the optimistic and conservative scenarios, mainly due to the impacts of landfilling. In the other impact categories, the difference between the scenarios is lower but still cannot be neglected (between 2 and 5 times).

For the global warming potential and resources depletion impact categories, the optimistic scenario resulted in higher impacts mainly due to the energy consumption and chemical products used in the recycling processes. Regarding the global warming potential, Menikpura and colleagues have also identified significant CO_{2eq} emissions when assessing the impacts of WEEE recycling in Tokyo, mainly from WEEE smelting process (Menikpura, Santo, & Hotta, 2014). For the impact categories of freshwater ecotoxicity and human toxicity (cancer and non-cancer effects), the pessimist scenario led to higher impacts considering that 78.5% of the tablet was landfilled. The processes responsible for higher toxicity impacts were battery, LCD module and copper landfilling.

Table 4. LCIA results: environmental impacts of treating 1 ton of tablet

Impact category	Unit	Optimistic scenario	Conservative scenario	Pessimist scenario
Global Warming Potential	$kgCO_{2eq}$	359.69	350.06	85.20
Human toxicity, non-cancer effects	CTUh	0.0047	0.0048	0.0464
Human toxicity, cancer effects	CTUh	0.0001	0.0001	0.0003
Freshwater ecotoxicity	CTUe	3.76E+06	4.04E+6	5.44E+6
Mineral, fossil and renewable resource depletion	$KgSb_{eq}$	0.0225	0.0225	0.0051

When comparing the results of the optimistic and the conservative scenario in **Table 3**, there is a difference of 16.5% of the total materials recycled in optimistic and conservative scenarios, mainly due to the recycling of the LCD glass (it represents 19.3% of the tablets mass). However, there is not a significant growth of environmental impact with the increase of recycling (**Table 4**). Further, for the impact categories related to toxicity, the optimistic scenario resulted in lower impacts once less material was landfilled. This result reinforces the benefits of improve recycling.

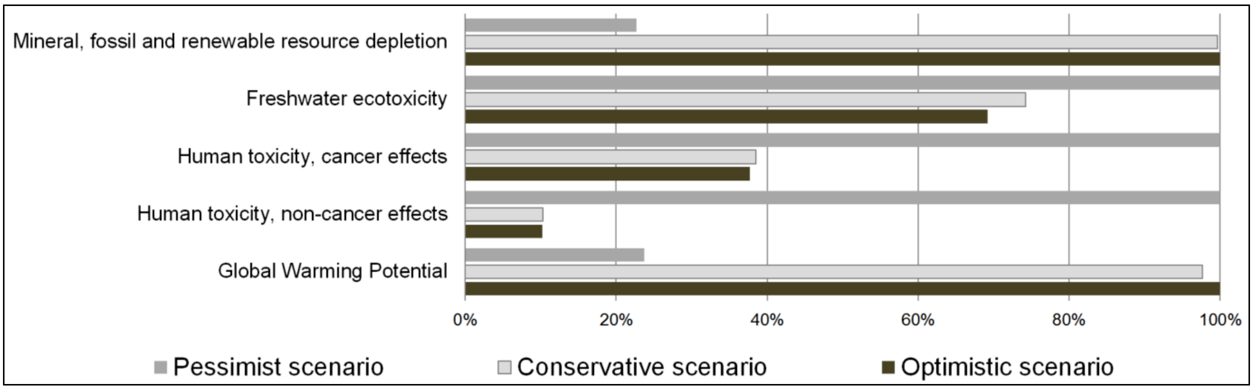

Figure 2. Environmental impacts of treating 1 ton of tablet (higher result in each impact category is set as 100%)

In the second step of the LCIA, in order to assess the benefits of recycling, the impacts of the EoL were compared to the production of virgin materials. Based on the amounts of recycled materials resulted from the recycling activities of the EoL scenarios, the impact of producing the same amount of virgin materials was assessed. For example, the “Optimistic scenario – Avoided impacts” accounts for the impacts of producing the same amount of metals and plastics recycled in the scenario “Optimistic scenario”. The impact of producing the energy generated from the incineration with energy recovery of sorting and recycling losses and plastic from PCB was equally taken into account.

As presented in Figure 3, the impact of producing the virgin materials is significantly higher than the impact of the EoL process itself, with the exception of freshwater ecotoxicity, where the treatment process is higher than the production of the virgin materials due to the impacts of landfilling. These results reinforce the benefits of improving WEEE recycling in order to reduce the destination of e-waste to landfills. Additionally, the results foster the discussion of the importance of the recycling channels as a provider of secondary materials that would have lower impacts in comparison with the production of virgin materials.

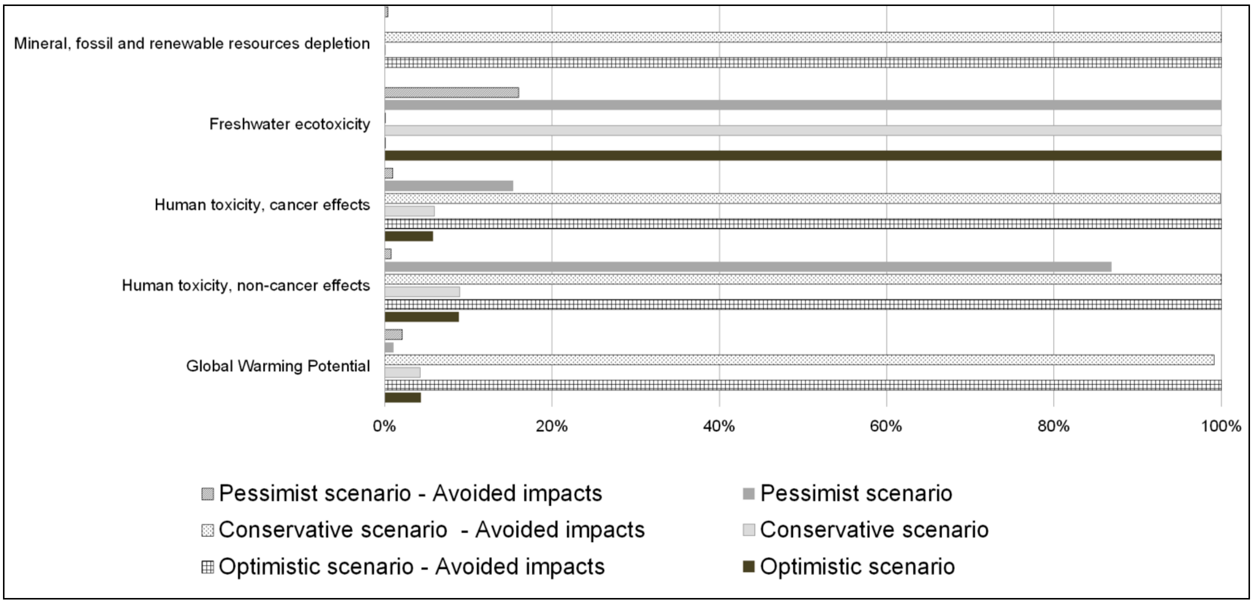

Figure 3. Comparison between the environmental impacts of the treatment scenarios and the production of primary materials (higher result in each impact category is set as 100%)

Among the LCA of (W)EEE published in literature identified in this study, two of them were applied to tablets: Achachlouei et al. (2015) and Hischier and Wäger (2015). The system boundary of both studies included the tablet production, use and EoL, but only the study presented by Achachlouei and colleagues clearly stated the EoL scenario considered. This scenario is similar to our conservative scenario proposal, except for the LCD treatment (considered as 85% incineration and 15% recycling). The results of both studies were expressed in terms of the total impact (all life cycle stages), and the percentage of the result related to the EoL stage was not presented in details, so it was not possible to compare these results with our study. According to Hischier and Wäger, the only impact category for which EoL treatment is of relevance is freshwater ecotoxicity potential (the LCIA method used in the study was ReCiPe). In the present study, when normalizing the results, freshwater ecotoxicity is also the most relevant impact category. It is important to remark that the models used to assess freshwater ecotoxicity have uncertainties due to lack of toxicological data which entails on data extrapolation, for example, of chemicals, environmental media, or animal species.

5. CONCLUSIONS

Differences in an order of 10 times were identified when comparing the results of the different scenarios, so it can be concluded that EoL modeling can impact the final results of a LCA study, so methodological choices must be clearly reported.

It is also recommended to select more realistic scenarios considering the current practices of waste management specific to each country. As mentioned by Achachlouei and colleagues (2015), there is an absence of WEEE EoL data in LCA databases, so it is important to enlarge and update the data available to encourage LCA practitioners to better take account of this stage in LCA studies.

In order to assess the benefits of recycling as a potential reducer of virgin materials production and resources extraction, the results of the environmental impacts of the treatment activities were compared to the virgin material production. With exception of freshwater ecotoxicity, the impacts of primary materials extraction were significantly higher than the impacts of tablet's EoL. This comparison allowed a first overview of the impacts, however, it is known that this method has limitations, and the potential benefits should also be assessed considering other methods, for example ILCD and PEF methods. As previously mentioned, another limitation of this study was not to consider the impact of WEEE transport, aspect that will be studied by the authors in future works.

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